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Li

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(54) **METHOD AND SYSTEM FOR A LOCAL STORAGE ENGINE COLLABORATING WITH A SOLID STATE DRIVE CONTROLLER**

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https://web.archive.org/web/20071130235034/http://en.wikipedia.org:80/wiki/logical_block_addressing wikipedia screen shot retriefed on wayback Nov. 20, 2007 showing both physical and logical addressing used historically to access data on storage devices (Year: 2007).

(Continued)

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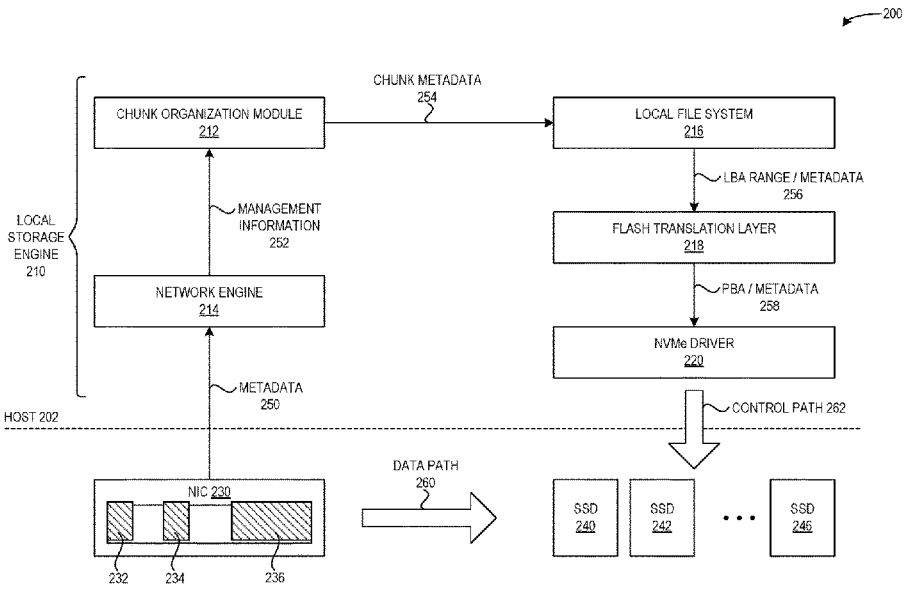
(57) **ABSTRACT**

One embodiment provides a system which facilitates data movement. The system allocates, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive or a first NIC. The first storage drive, the second storage drive, and the first NIC are associated with a first server. The system stores data in the first region. Responsive to receiving a first request from the second storage drive to read the data, the system transmits, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server. Responsive to receiving, from a third storage drive associated with a second server, a second request to read the data, the system retrieves, by the first NIC, the data stored in the first region while bypassing the system memory of the first server.

16 Claims, 11 Drawing Sheets



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2021/0124488	A1	4/2021	Stoica	
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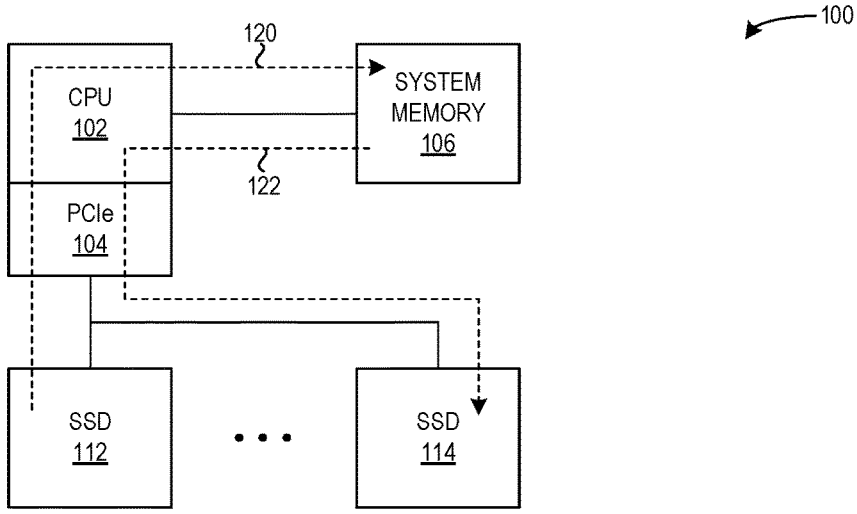


FIG. 1A (PRIOR ART)

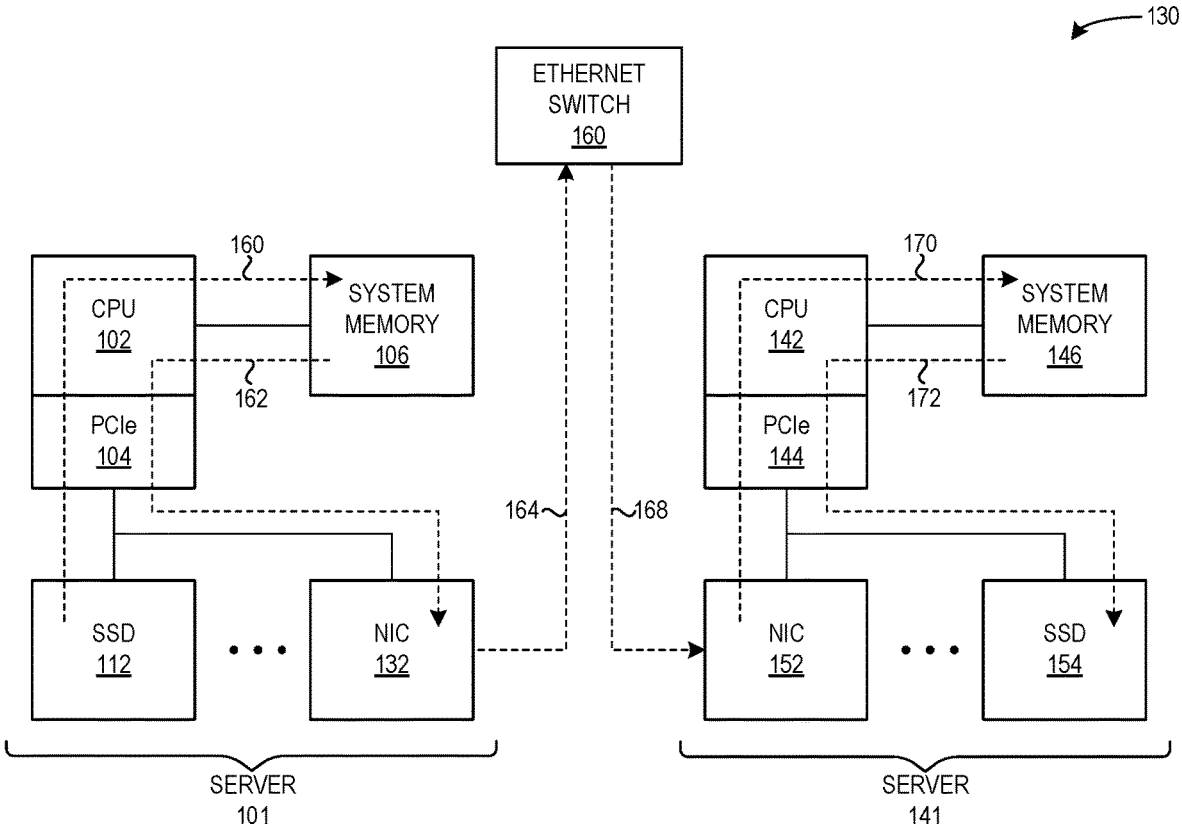


FIG. 1B (PRIOR ART)

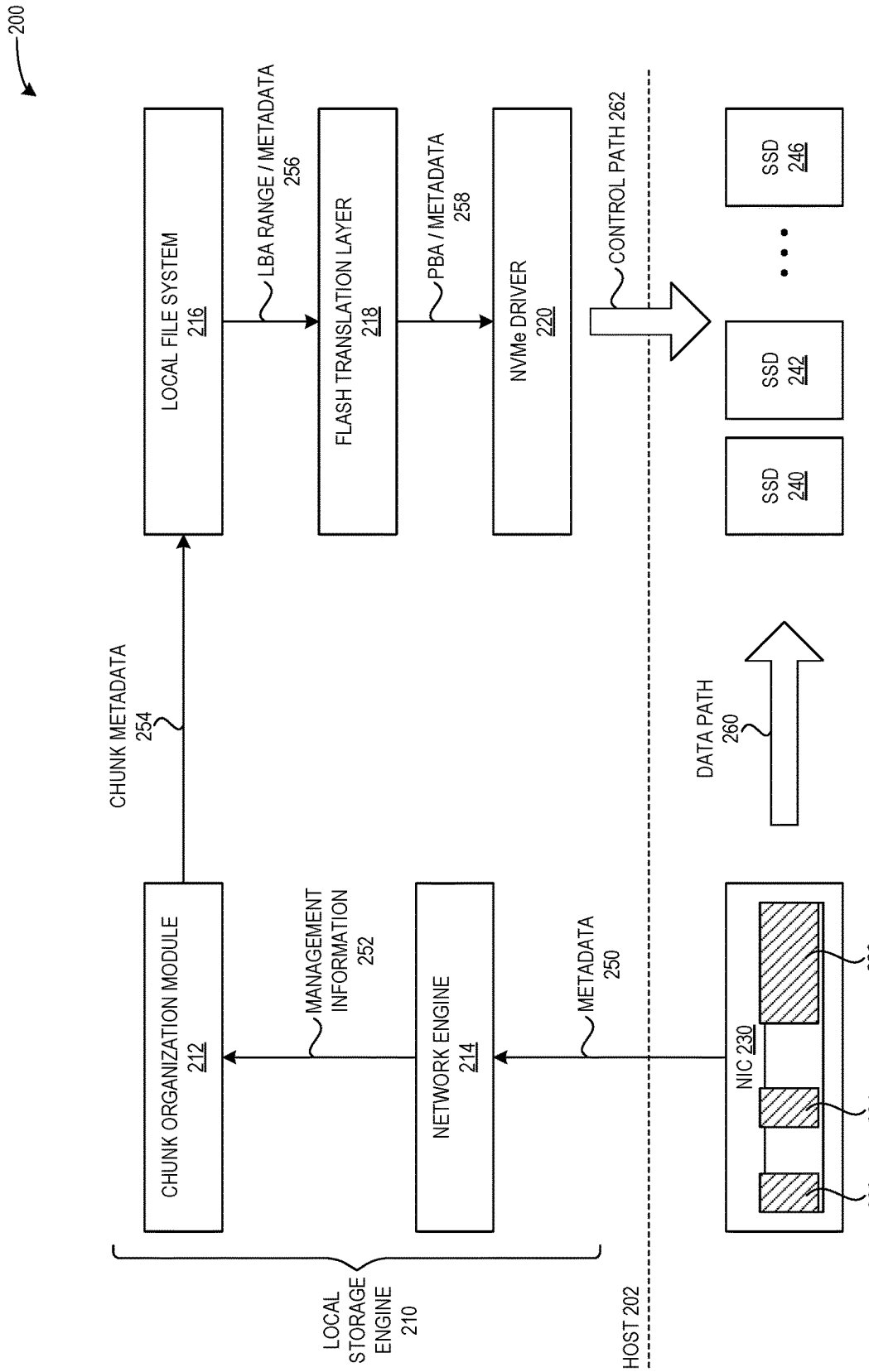

200
LOCAL FILE SYSTEM 216
LBA RANGE / METADATA 256
FLASH TRANSLATION LAYER 218
PBA / METADATA 258
NVMe DRIVER 220
CONTROL PATH 262
SSD 246
SSD 242
SSD 240
CHUNK METADATA 254
DATA PATH 260
CHUNK ORGANIZATION MODULE 212
MANAGEMENT INFORMATION 252
NETWORK ENGINE 214
METADATA 250
NIC 230
236
234
232
LOCAL STORAGE ENGINE 210
HOST 202

FIG. 2

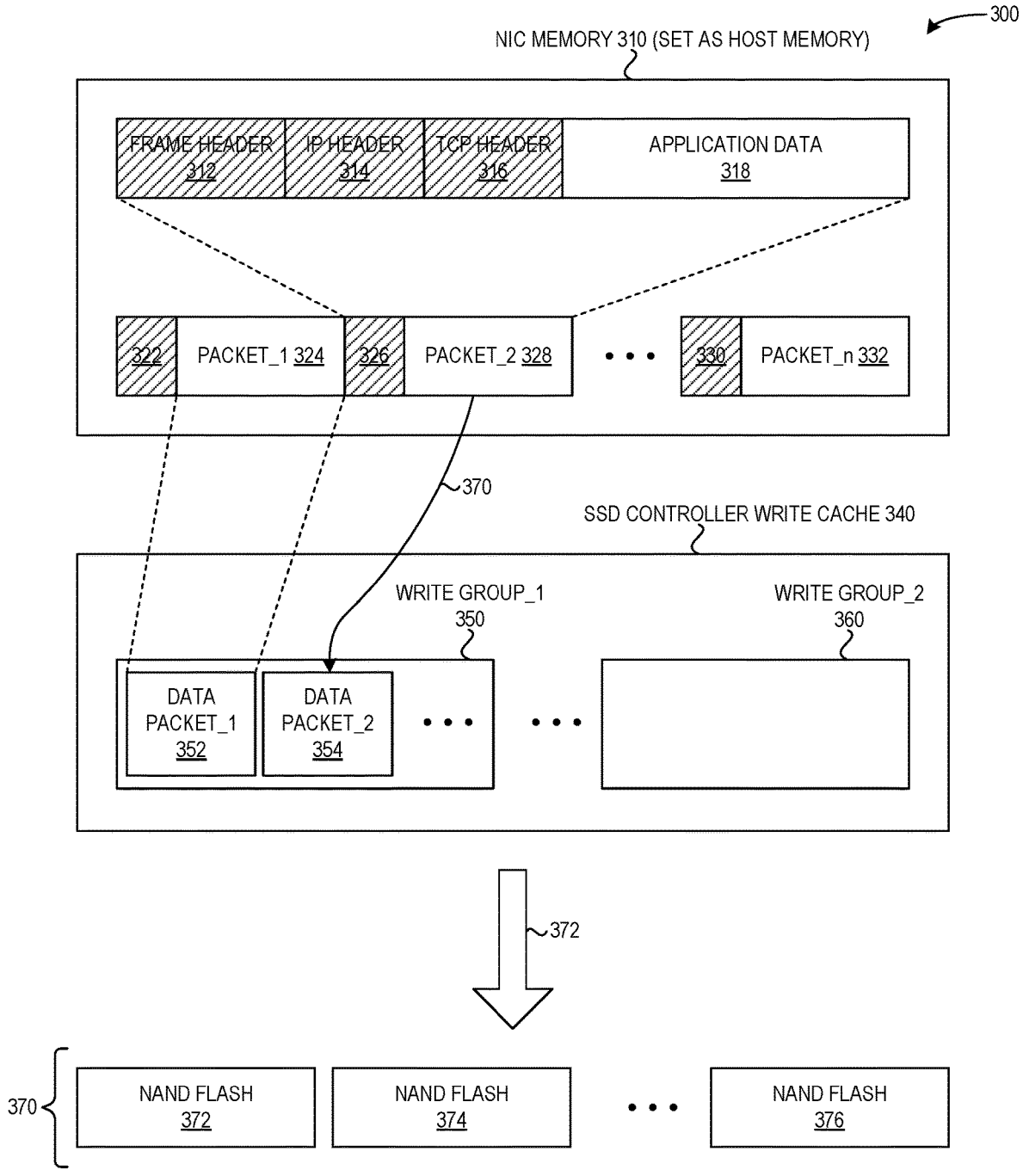

300
NIC MEMORY 310 (SET AS HOST MEMORY)
FRAME HEADER 312
IP HEADER 314
TCP HEADER 316
APPLICATION DATA 318
322
PACKET_1 324
326
PACKET_2 328
330
PACKET_n 332
370
SSD CONTROLLER WRITE CACHE 340
WRITE GROUP_1 350
WRITE GROUP_2 360
DATA PACKET_1 352
DATA PACKET_2 354
372
370
NAND FLASH 372
NAND FLASH 374
NAND FLASH 376

FIG. 3

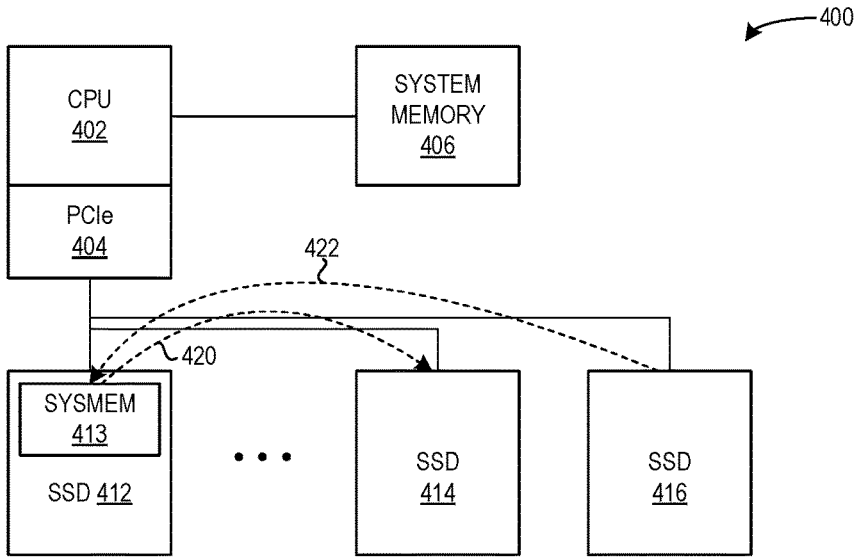

400
CPU
402
SYSTEM
MEMORY
406
PCIe
404
422
420
SYSMEM
413
SSD 412
SSD
414
SSD
416

FIG. 4A

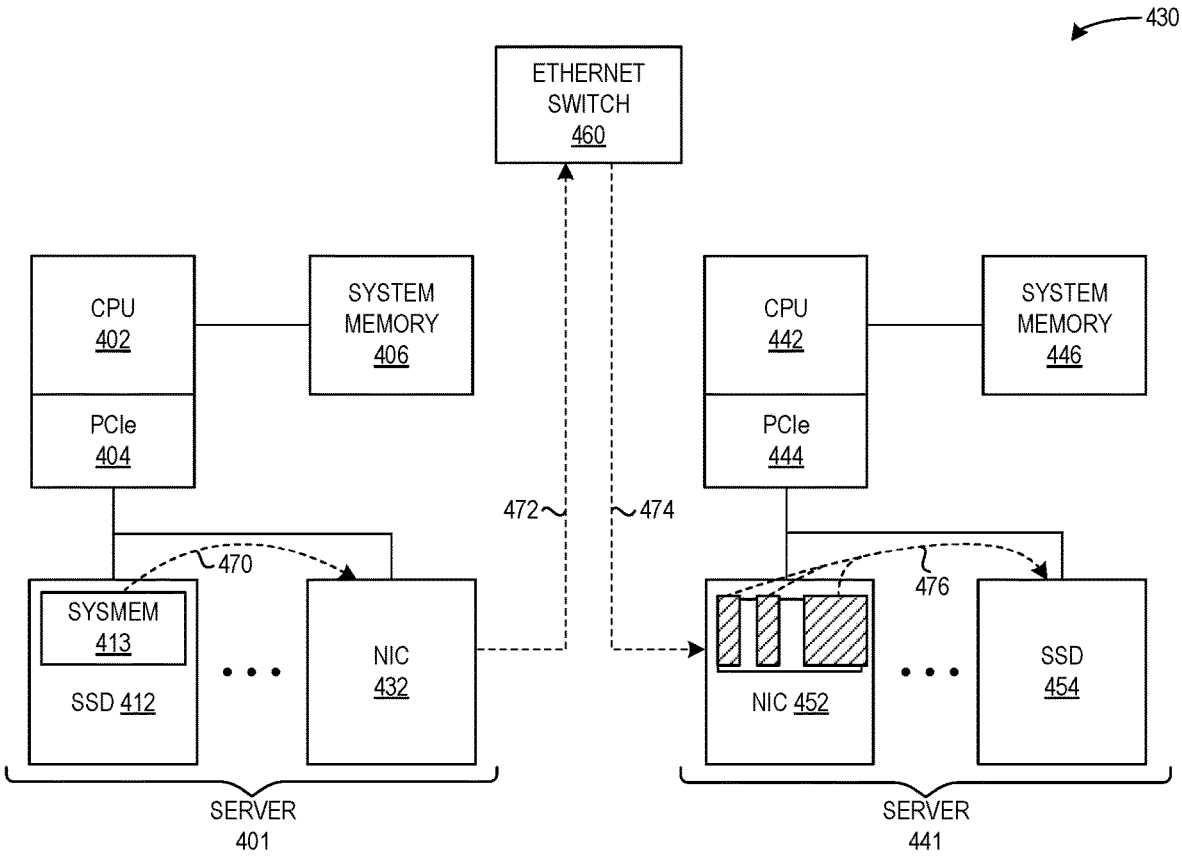

430
ETHERNET
SWITCH
460
CPU
402
SYSTEM
MEMORY
406
PCIe
404
CPU
442
SYSTEM
MEMORY
446
PCIe
444
472
474
470
476
SYSMEM
413
SSD 412
NIC
432
NIC 452
SSD
454
SERVER
401
SERVER
441

FIG. 4B

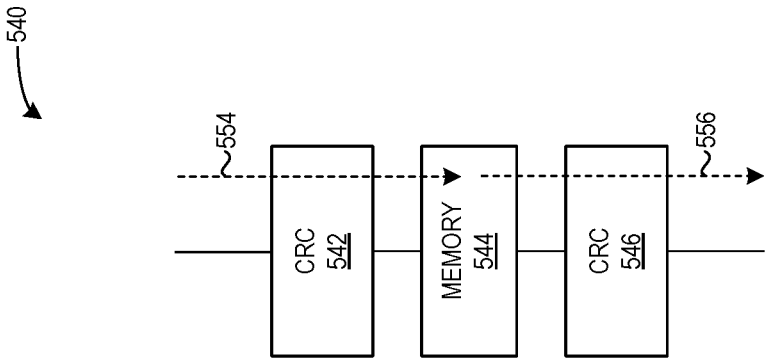

540
554
CRC
542
MEMORY
544
CRC
546
556

FIG. 5B

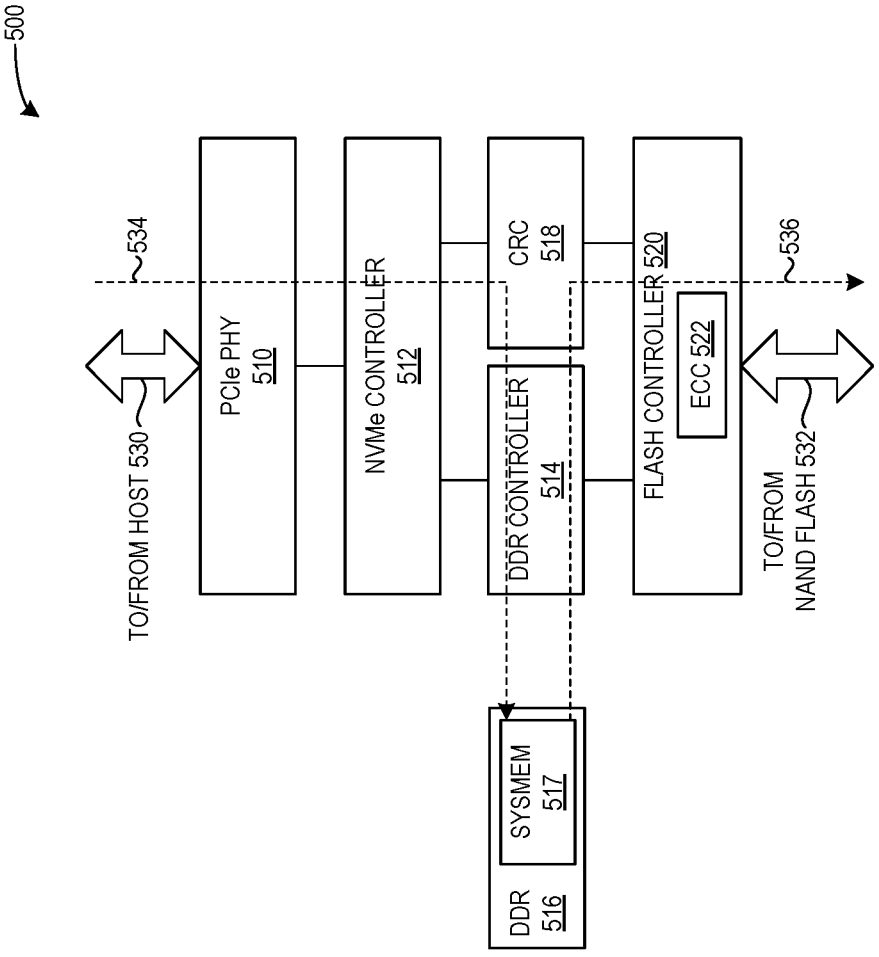

500
534
PCIe PHY
510
NVMe CONTROLLER
512
CRC
518
DDR CONTROLLER
514
FLASH CONTROLLER 520
ECC 522
536
TO/FROM HOST 530
TO/FROM
NAND FLASH 532
DDR
516
SYSMEM
517

FIG. 5A

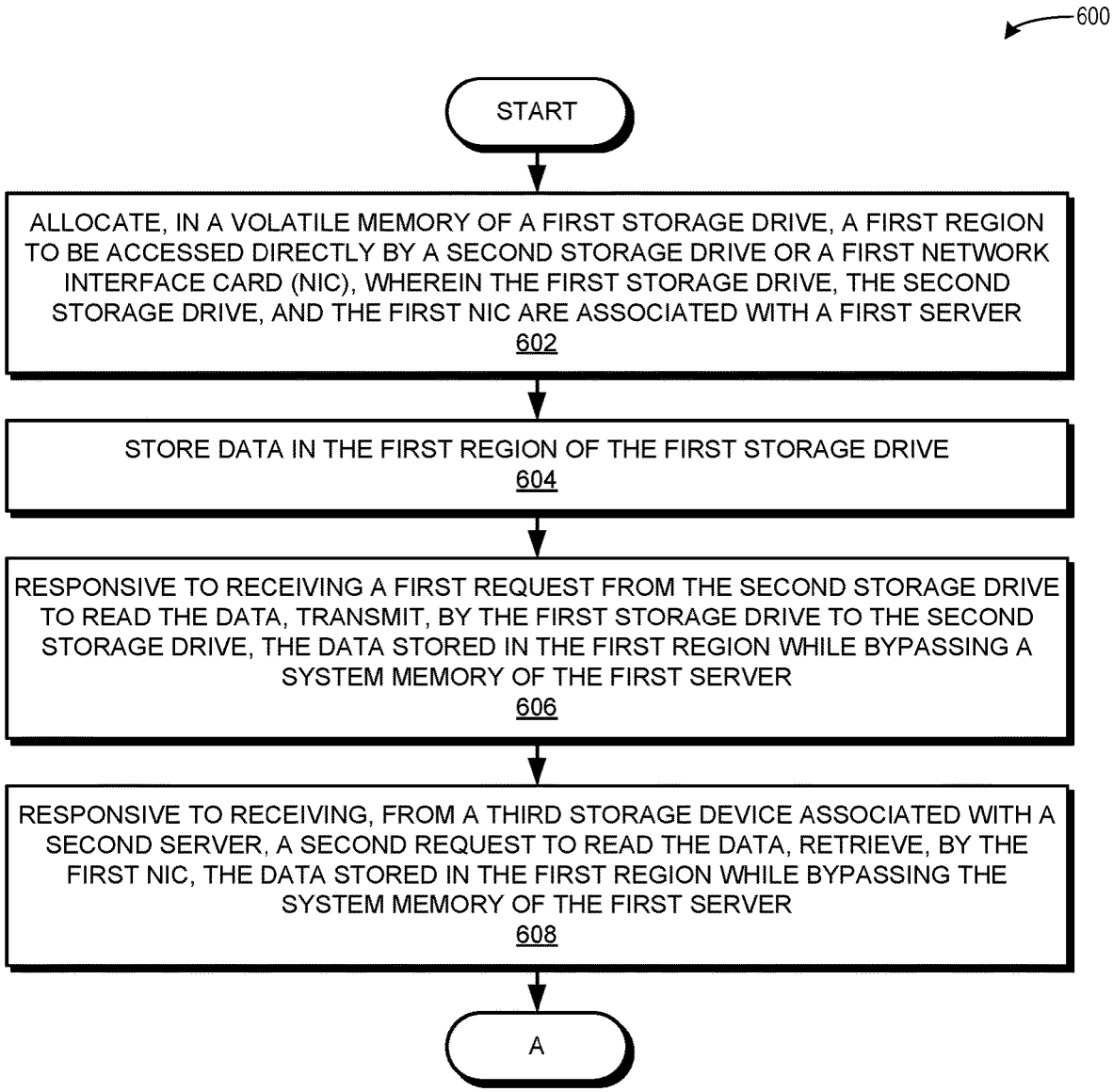

600
START
ALLOCATE, IN A VOLATILE MEMORY OF A FIRST STORAGE DRIVE, A FIRST REGION TO BE ACCESSED DIRECTLY BY A SECOND STORAGE DRIVE OR A FIRST NETWORK INTERFACE CARD (NIC), WHEREIN THE FIRST STORAGE DRIVE, THE SECOND STORAGE DRIVE, AND THE FIRST NIC ARE ASSOCIATED WITH A FIRST SERVER
602
STORE DATA IN THE FIRST REGION OF THE FIRST STORAGE DRIVE
604
RESPONSIVE TO RECEIVING A FIRST REQUEST FROM THE SECOND STORAGE DRIVE TO READ THE DATA, TRANSMIT, BY THE FIRST STORAGE DRIVE TO THE SECOND STORAGE DRIVE, THE DATA STORED IN THE FIRST REGION WHILE BYPASSING A SYSTEM MEMORY OF THE FIRST SERVER
606
RESPONSIVE TO RECEIVING, FROM A THIRD STORAGE DEVICE ASSOCIATED WITH A SECOND SERVER, A SECOND REQUEST TO READ THE DATA, RETRIEVE, BY THE FIRST NIC, THE DATA STORED IN THE FIRST REGION WHILE BYPASSING THE SYSTEM MEMORY OF THE FIRST SERVER
608
A

FIG. 6A

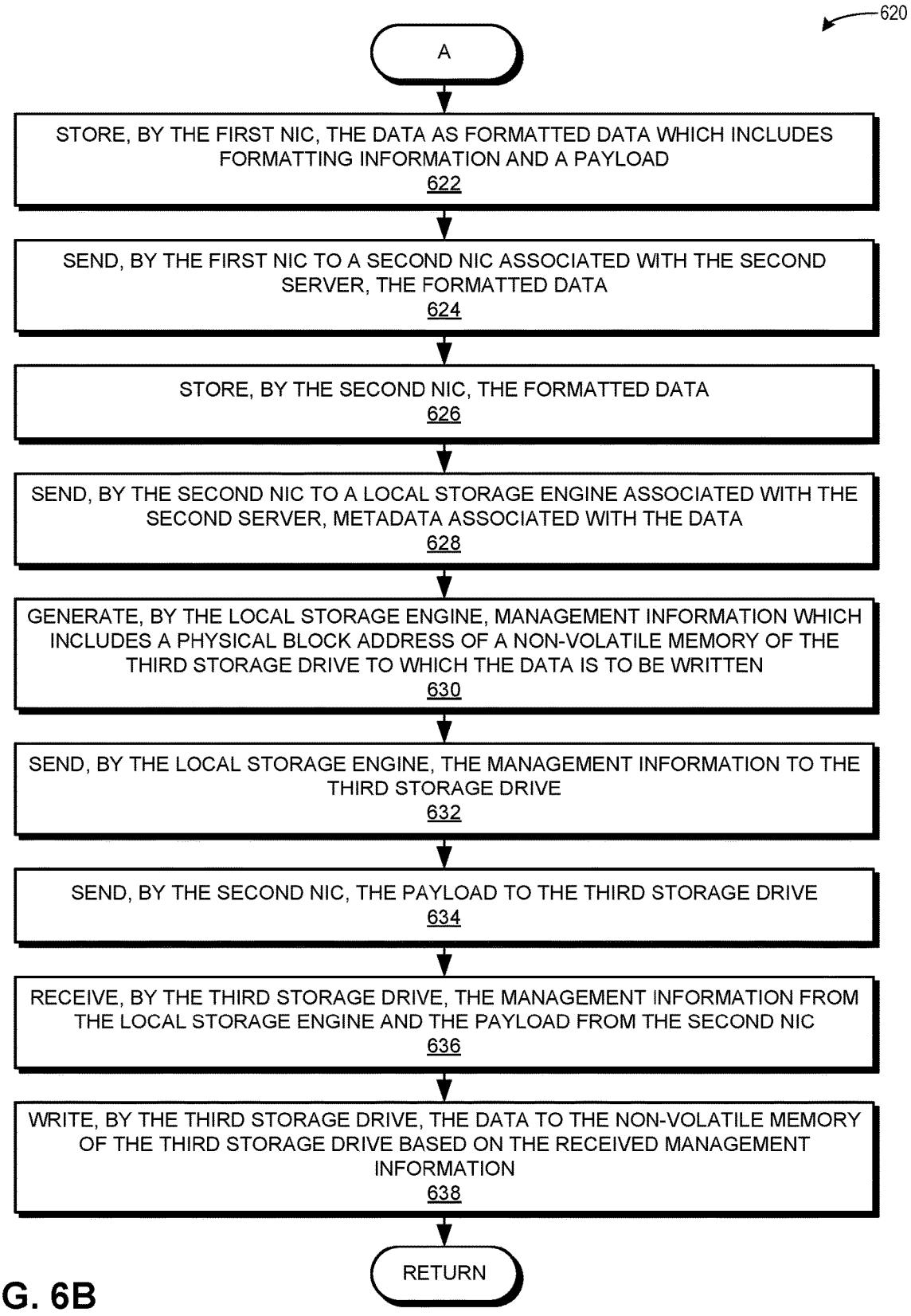

620
A
STORE, BY THE FIRST NIC, THE DATA AS FORMATTED DATA WHICH INCLUDES FORMATTING INFORMATION AND A PAYLOAD
622
SEND, BY THE FIRST NIC TO A SECOND NIC ASSOCIATED WITH THE SECOND SERVER, THE FORMATTED DATA
624
STORE, BY THE SECOND NIC, THE FORMATTED DATA
626
SEND, BY THE SECOND NIC TO A LOCAL STORAGE ENGINE ASSOCIATED WITH THE SECOND SERVER, METADATA ASSOCIATED WITH THE DATA
628
GENERATE, BY THE LOCAL STORAGE ENGINE, MANAGEMENT INFORMATION WHICH INCLUDES A PHYSICAL BLOCK ADDRESS OF A NON-VOLATILE MEMORY OF THE THIRD STORAGE DRIVE TO WHICH THE DATA IS TO BE WRITTEN
630
SEND, BY THE LOCAL STORAGE ENGINE, THE MANAGEMENT INFORMATION TO THE THIRD STORAGE DRIVE
632
SEND, BY THE SECOND NIC, THE PAYLOAD TO THE THIRD STORAGE DRIVE
634
RECEIVE, BY THE THIRD STORAGE DRIVE, THE MANAGEMENT INFORMATION FROM THE LOCAL STORAGE ENGINE AND THE PAYLOAD FROM THE SECOND NIC
636
WRITE, BY THE THIRD STORAGE DRIVE, THE DATA TO THE NON-VOLATILE MEMORY OF THE THIRD STORAGE DRIVE BASED ON THE RECEIVED MANAGEMENT INFORMATION
638
RETURN

FIG. 6B

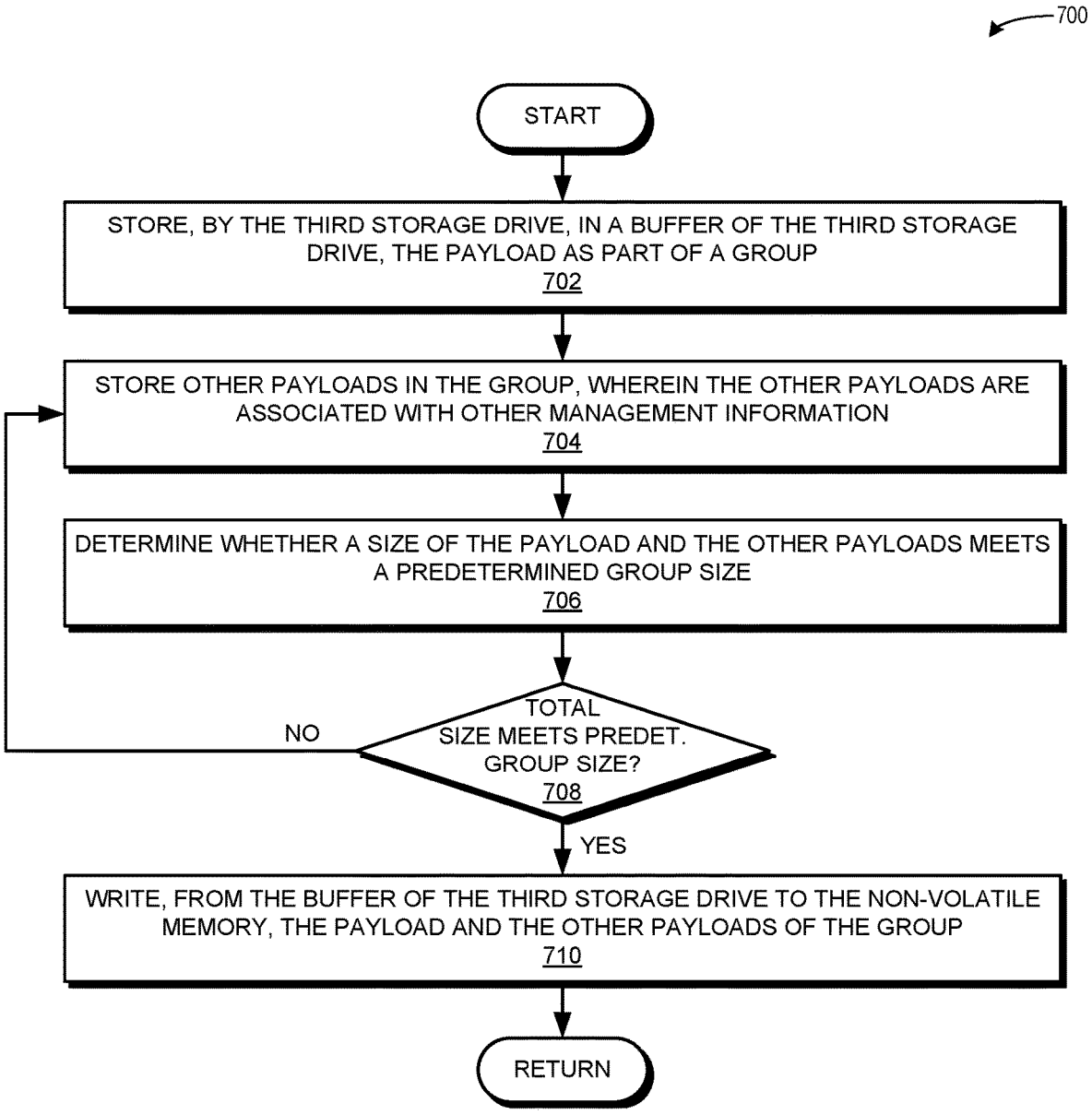

700
START
STORE, BY THE THIRD STORAGE DRIVE, IN A BUFFER OF THE THIRD STORAGE DRIVE, THE PAYLOAD AS PART OF A GROUP
702
STORE OTHER PAYLOADS IN THE GROUP, WHEREIN THE OTHER PAYLOADS ARE ASSOCIATED WITH OTHER MANAGEMENT INFORMATION
704
DETERMINE WHETHER A SIZE OF THE PAYLOAD AND THE OTHER PAYLOADS MEETS A PREDETERMINED GROUP SIZE
706
TOTAL SIZE MEETS PREDET. GROUP SIZE?
708
NO
YES
WRITE, FROM THE BUFFER OF THE THIRD STORAGE DRIVE TO THE NON-VOLATILE MEMORY, THE PAYLOAD AND THE OTHER PAYLOADS OF THE GROUP
710
RETURN

FIG. 7

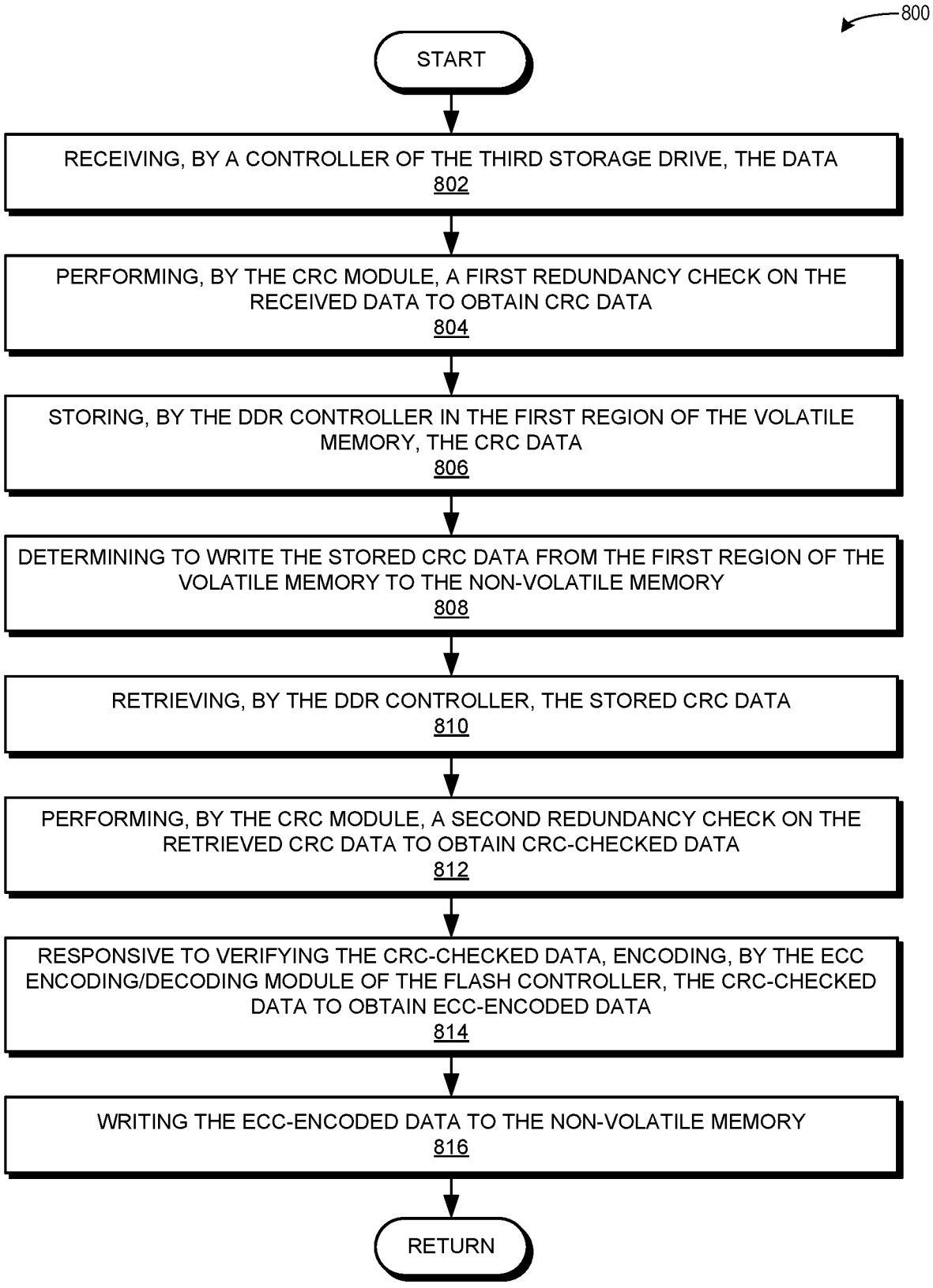
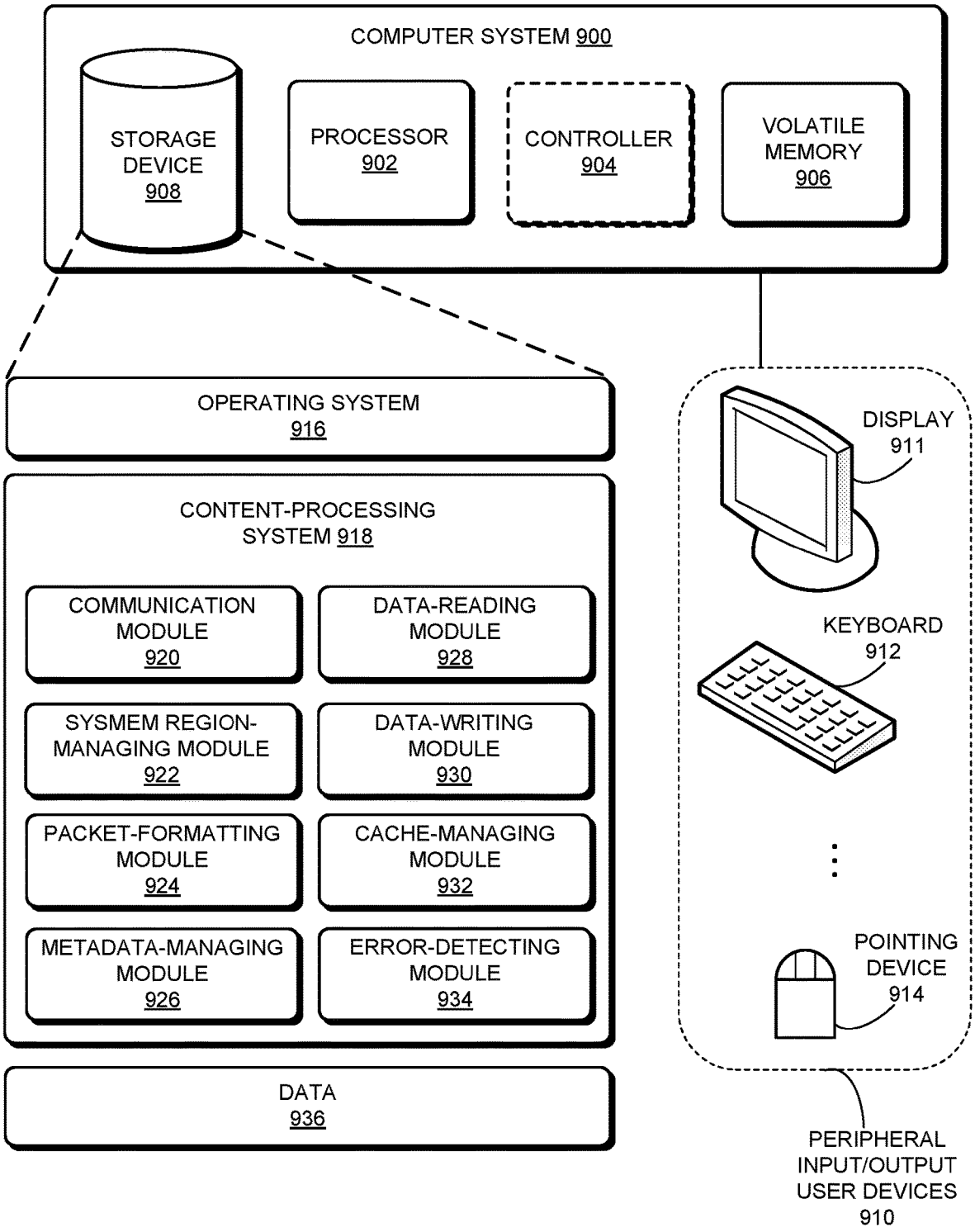

800
START
RECEIVING, BY A CONTROLLER OF THE THIRD STORAGE DRIVE, THE DATA
802
PERFORMING, BY THE CRC MODULE, A FIRST REDUNDANCY CHECK ON THE RECEIVED DATA TO OBTAIN CRC DATA
804
STORING, BY THE DDR CONTROLLER IN THE FIRST REGION OF THE VOLATILE MEMORY, THE CRC DATA
806
DETERMINING TO WRITE THE STORED CRC DATA FROM THE FIRST REGION OF THE VOLATILE MEMORY TO THE NON-VOLATILE MEMORY
808
RETRIEVING, BY THE DDR CONTROLLER, THE STORED CRC DATA
810
PERFORMING, BY THE CRC MODULE, A SECOND REDUNDANCY CHECK ON THE RETRIEVED CRC DATA TO OBTAIN CRC-CHECKED DATA
812
RESPONSIVE TO VERIFYING THE CRC-CHECKED DATA, ENCODING, BY THE ECC ENCODING/DECODING MODULE OF THE FLASH CONTROLLER, THE CRC-CHECKED DATA TO OBTAIN ECC-ENCODED DATA
814
WRITING THE ECC-ENCODED DATA TO THE NON-VOLATILE MEMORY
816
RETURN

FIG. 8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STORAGE DEVICE 908
PROCESSOR 902
CONTROLLER 904
VOLATILE MEMORY 906
OPERATING SYSTEM 916
CONTENT-PROCESSING SYSTEM 918
COMMUNICATION MODULE 920
DATA-READING MODULE 928
SYSMEM REGION-MANAGING MODULE 922
DATA-WRITING MODULE 930
PACKET-FORMATTING MODULE 924
CACHE-MANAGING MODULE 932
METADATA-MANAGING MODULE 926
ERROR-DETECTING MODULE 934
DATA 936
DISPLAY 911
KEYBOARD 912
POINTING DEVICE 914
PERIPHERAL INPUT/OUTPUT USER DEVICES 910

FIG. 9

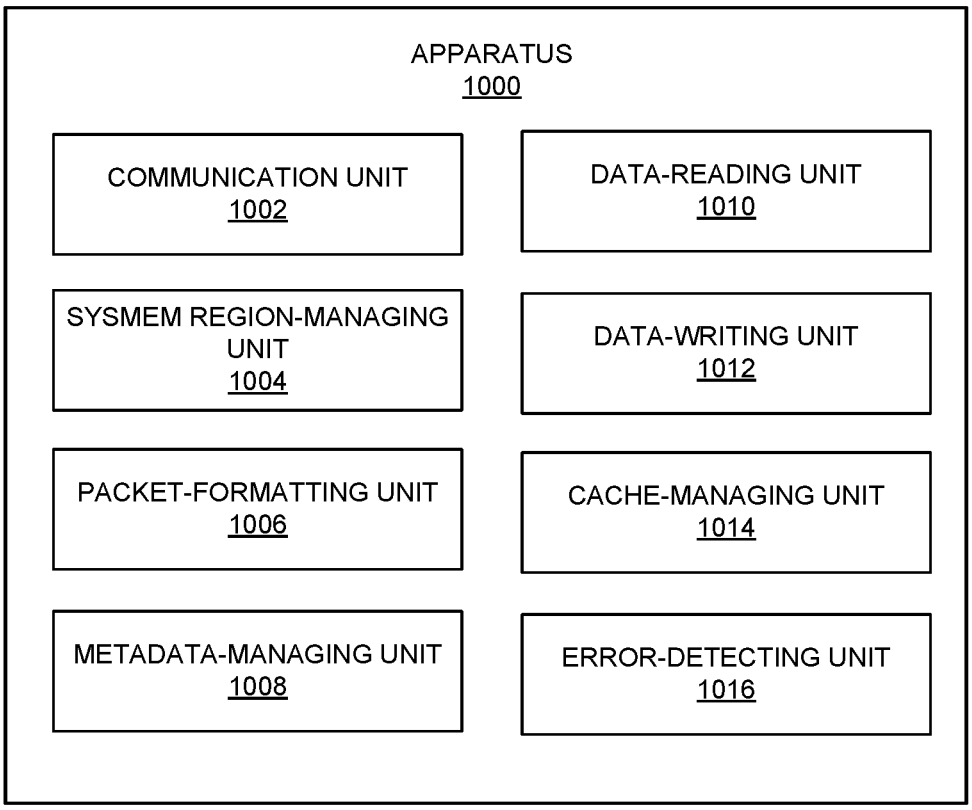
APPARATUS
1000
COMMUNICATION UNIT
1002
DATA-READING UNIT
1010
SYSMEM REGION-MANAGING UNIT
1004
DATA-WRITING UNIT
1012
PACKET-FORMATTING UNIT
1006
CACHE-MANAGING UNIT
1014
METADATA-MANAGING UNIT
1008
ERROR-DETECTING UNIT
1016

FIG. 10

METHOD AND SYSTEM FOR A LOCAL STORAGE ENGINE COLLABORATING WITH A SOLID STATE DRIVE CONTROLLER

BACKGROUND

Field

This disclosure is generally related to the field of data storage. More specifically, this disclosure is related to a method and system for a local storage engine collaborating with a solid state drive (SSD) controller.

Related Art

Today, various storage systems are being used to store and access the ever-increasing amount of digital content. A storage system can include storage servers with one or more storage devices or drives (such as a solid-state drive (SSD)). In the architecture of an existing storage system, a central processing unit (CPU) complex can include a CPU and system memory, which can serve as the data hub. Data transfers both within a storage server (e.g., between storage drives of the same storage server) and between storage servers (e.g., between storages drive of different storage servers) can result in multiple folds of memory copy which involve the CPU and system memory. These data transfers can result in an increased latency, an increased consumption of memory bandwidth, and an increased utilization of the CPU complex or core. In scenarios which involve a large amount of data transfer, the system performance and resource consumption can suffer and limit the efficiency of the overall storage system.

SUMMARY

One embodiment provides a system which facilitates data movement while bypassing the system memory. During operation, the system allocates, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive. The system stores data in the first region of the first storage drive. Responsive to receiving a first request from the second storage drive to read the data, the system transmits, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of a first server.

In some embodiments, the first storage drive and the second storage drive are associated with the first server.

In some embodiments, the first region of the first storage drive is to be further accessed by a third storage drive via a first network interface card (NIC). The first NIC is associated with the first server, and the third storage drive is associated with a second server

In some embodiments, responsive to receiving, from the third storage drive, a second request to read the data, the system retrieves, by the first NIC, the data stored in the first region while bypassing the system memory of the first server. The system stores, by the first NIC, the data as formatted data which includes formatting information and a payload. The system sends, by the first NIC to a second NIC associated with the second server, the formatted data. The system stores, by the second NIC, the formatted data. The system sends, by the second NIC to a local storage engine associated with the second server, metadata associated with the data. The system generates, by the local storage engine, management information which includes a physical block address of a non-volatile memory of the third storage drive to which the data is to be written. The system sends, by the local storage engine, the management information to the third storage drive. The system sends, by the second NIC, the payload to the third storage drive. The system receives, by the third storage drive, the management information from the local storage engine and the payload from the second NIC. The system writes, by the third storage drive, the data to the non-volatile memory of the third storage drive based on the received management information.

In some embodiments, the formatting information includes one or more of a frame header, an Internet Protocol (IP) header, and a Transmission Control Protocol (TCP) header. The payload includes one or more of application data and user data. Sending, by the first NIC to the second NIC, the formatted data further involves sending the formatted data through an Ethernet switch.

In some embodiments, the system sets, in the second NIC, a second region of a volatile memory of the second NIC as a host memory which is directly accessible by the third storage drive. The system stores, by the second NIC, the formatted data in the second region of the second NIC.

In some embodiments, subsequent to sending, by the second NIC to the local storage engine, the metadata, the system performs the following operations. The system generates, by a network engine of the local storage engine, the management information, which includes one or more of an order and a merged size. The system groups, by a chunk organization module of the local storage engine, multiple chunks of data in parallel. The system allocates, by a local file system of the local storage engine, a logical extent or a range of logical block addresses (LBAs) based on metadata associated with the multiple chunks. The system sends, by the file system to a flash translation layer module of the local storage engine, the allocated LBAs. The system receives, by the flash translation layer module, the allocated LBAs. The system generates, by the flash translation layer module, physical block addresses (PBAs) mapped to the allocated LBAs. The system transmits, by the flash translation layer module to a Non-Volatile Memory Express (NVMe) driver, the PBAs and the metadata. The system transmits, by the NVMe driver to a controller of the third storage drive, the PBAs and the metadata.

In some embodiments, the system writes, by the third storage drive, the data to the non-volatile memory based on the received management information by performing the following operations. The system stores, by the third storage drive, in a buffer of the third storage drive, the payload as part of a group. The system stores other payloads in the group, wherein the other payloads are associated with other management information. The system determines that a size of the payload and the other payloads meets a predetermined group size. The system writes, from the buffer of the third storage drive to the non-volatile memory, the payload and the other payloads of the group.

In some embodiments, the system writes, by the third storage drive, the data to the non-volatile memory by performing the following operations. The system receives, by a controller of the third storage drive, the data. The controller includes a Non-Volatile Memory Express (NVMe) controller, a double data rate (DDR) controller associated with the volatile memory, a cyclic redundancy check (CRC) module, and a flash controller, wherein the flash controller includes an error correction code (ECC) encoding/decoding module. The system performs, by the CRC module, a first redundancy check on the received data to obtain CRC data. The system stores, by the DDR con-

troller in the first region of the volatile memory, the CRC data. The system determines to write the stored CRC data from the first region of the volatile memory to the non-volatile memory. The system retrieves, by the DDR controller, the stored CRC data. The system performs, by the CRC module, a second redundancy check on the retrieved CRC data to obtain CRC-checked data. Responsive to verifying the CRC-checked data, the system encodes, by the ECC encoding/decoding module of the flash controller, the CRC-checked data to obtain ECC-encoded data. The system writes the ECC-encoded data to the non-volatile memory.

In some embodiments, the data stored in the first region of the first storage drive is transferred from the second storage drive or the first NIC while bypassing the system memory of the first server.

In some embodiments, subsequent to the first storage drive transmitting to the second storage drive the data stored in the first region while bypassing the system memory of the first server, the system retrieves, by the second storage drive, the data stored in the first region while bypassing the system memory of the first server.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A illustrates an exemplary environment with a data transfer between storage drives in a same storage server, in accordance with the prior art.

FIG. **1**B illustrates an exemplary environment with a data transfer between storage drives in different storage servers, in accordance with the prior art.

FIG. **2** illustrates an exemplary environment with separate control and data paths, which facilitates bypassing system memory, in accordance with an embodiment of the present application.

FIG. **3** illustrates an exemplary environment with data movement from a network interface card to a storage drive, in accordance with an embodiment of the present application.

FIG. **4**A illustrates an exemplary environment with a data transfer between storage drives in a same storage server, which facilitates bypassing system memory, in accordance with an embodiment of the present application.

FIG. **4**B illustrates an exemplary environment with a data transfer between storage drives in different storage servers, which facilitates bypassing system memory, in accordance with an embodiment of the present application.

FIG. **5**A illustrates an exemplary environment for data access with a cyclic redundancy check (CRC) in a storage controller, in accordance with an embodiment of the present application.

FIG. **5**B illustrates an exemplary environment for data access with a CRC in a storage controller, in accordance with an embodiment of the present application.

FIG. **6**A presents a flowchart illustrating a method for facilitating data movement while bypassing system memory, including a data transfer between storage drives in a same storage server, in accordance with an embodiment of the present application.

FIG. **6**B presents a flowchart illustrating a method for facilitating data movement while bypassing system memory, including a data transfer between storage drives in different storage servers, in accordance with an embodiment of the present application.

FIG. **7** presents a flowchart illustrating a method for facilitating data movement while bypassing system memory, including writing data in groups to a non-volatile memory, in accordance with an embodiment of the present application.

FIG. **8** presents a flowchart illustrating a method for facilitating data movement while bypassing system memory, including operations to ensure data integrity, in accordance with an embodiment of the present application.

FIG. **9** illustrates an exemplary computer system that facilitates data movement while bypassing system memory, in accordance with an embodiment of the present application.

FIG. **10** illustrates an exemplary apparatus that facilitates data movement by bypassing system memory, in accordance with an embodiment of the present application.

In the figures, like reference numerals refer to the same figure elements.

DETAILED DESCRIPTION

The following description is presented to enable any person skilled in the art to make and use the embodiments, and is provided in the context of a particular application and its requirements. Various modifications to the disclosed embodiments will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the present disclosure. Thus, the embodiments described herein are not limited to the embodiments shown, but are to be accorded the widest scope consistent with the principles and features disclosed herein.

Overview

The embodiments described herein provide a system which addresses the inefficiencies associated with data transfers in existing storage systems which consume CPU resources and system memory bandwidth, by providing a system which bypasses the system memory.

As described above, in existing storage systems, a CPU complex can include a CPU and system memory, which can serve as the data hub. Data transfers both within a storage server (e.g., between storage drives of the same storage server) and between storage servers (e.g., between storages drive of different storage servers) can result in multiple folds of memory copy which involve the CPU and system memory, as described below in relation to FIGS. **1**A and **1**B. These data transfers can result in an increased latency, an increased consumption of memory bandwidth, and an increased utilization of the CPU complex or core. In scenarios which involve a large amount of data transfer, the system performance and resource consumption can suffer and limit the efficiency of the overall storage system.

The embodiments described herein address these limitations by providing a system which separates the data path and the control path, by allocating or exposing a portion of a volatile memory of a first SSD as a region which can be directly accessed by a second SSD (in a single server scenario, as described below in relation to FIG. **4**A) or a network interface card (NIC) (in a storage cluster scenario, as described below in relation to FIG. **4**B).

In the single server scenario (where the first and second SSD are associated with the same single server), the first SSD can allocate a region of its volatile memory to be directly accessible by other SSDs (and a NIC) associated with the same single server. The second SSD can subsequently directly access and retrieve data stored in the allocated region of the first SSD, which allows the data transfer to bypass the system memory of the server.

In the storage cluster scenario, when data is transferred from a first storage drive of a first storage server to a second storage drive of a second storage server, the data can pass through a first NIC of the first storage server and a second NIC of the second storage server. Formatting and retrieval of data from the NICs can be used to bypass the system memory, which can result in a more efficient overall storage system.

For example, for data which is to be transferred from the first storage drive to the second storage drive, the first NIC can retrieve the data directly from the allocated region of the first storage drive, while bypassing the system memory. The first NIC can format the data (e.g., into a network packet with formatting information and a payload), and transmit the network packet to the second NIC (e.g., via an Ethernet switch). In the control path, the second NIC can send the metadata to a local storage engine of the second server, which can perform management operations as described below in relation to FIG. **2**, and the local storage engine can send the management information (such as the metadata and an assigned physical block address (PBA)) to the second storage drive. In the data path, the second NIC can send to the second storage drive (and the second storage drive can receive or retrieve from the second NIC) the data as the payload only directly from the second NIC, again bypassing the system memory.

Thus, by allocating a region of the non-volatile memory of a first storage drive and making the allocated region directly accessible to a second storage drive in the same first server, the system can bypass system memory of the first server in the single server scenario. Furthermore, by allocating the region of the first storage drive and making the allocated region directly accessible to the first NIC (e.g., in the same first server), and by allowing data stored in a second NIC to be accessible by a third storage drive in the same second server (e.g., data stored in the second NIC is accessible by the third storage drive in the second server), the system can also bypass system memory in the storage cluster scenario.

The described embodiments can also perform consecutive data fetching based on groups in a write cache of the SSD controller, as described below in relation to FIG. **3**. In addition, the described embodiments can ensure the integrity of the data stored in the volatile memory of a storage drive, as described below in relation to FIG. **5**.

A "distributed storage system" or a "storage system" can include multiple storage servers. A "storage server" or a "storage system" can refer to a computing device which can include multiple storage devices or storage drives. A "storage device" or a "storage drive" refers to a device or a drive with a non-volatile memory which can provide persistent storage of data, e.g., a solid-state drive (SSD), or a flash-based storage device. A storage system can also be a computer system.

"Non-volatile memory" refers to storage media which may be used for persistent storage of data, e.g., flash memory of a NAND die of an SSD, magnetoresistive random access memory (MRAM), phase change memory (PCM), resistive random access memory (ReRAM), or another non-volatile memory.

"Volatile memory" refers to storage media which can include, e.g., dynamic random access memory (DRAM), double data rate (DDR) DRAM, and DDR dual in-line memory modules (DIMM). In general, data stored in volatile memory is not protected in the event of a power loss or other failure. In some cases, volatile memory can be protected from such data loss with a power protection module or other power loss component.

The terms "sysmem" and "region of a volatile memory" are used interchangeably in this disclosure and refer to a portion of a volatile memory of a first storage drive, where the portion or region is allocated to be accessed directly by a second storage drive or a NIC, and where the first storage drive, the second storage drive, and the NIC are associated with the same server. The allocated sysmem or region can serve as system memory for the storage device in a more efficient manner than the conventional system memory associated with a host or a storage server.

A "computing device" refers to any server, device, node, entity, drive, or any other entity which can provide any computing capabilities.

The term "write cache" refers to a data cache, buffer, or region which can store data in a persistent memory or a non-volatile memory.

Exemplary Data Transfer in the Prior Art

FIG. **1**A illustrates an exemplary environment **100** with a data transfer between storage drives in a same storage server, in accordance with the prior art. Environment **100** can include: a central processing unit (CPU) **102**, an associated Peripheral Component Interconnect Express (PCIe) interface **104**, and an associated system memory **106**; and solid state drives (SSDs) **112** and **114**. CPU **102** can communicate with SSDs **112** and **114** via PCIe interface **104**. During operation, in order to move data from one drive to another drive (e.g., from a source drive such as SSD **112** to a destination drive such as SSD **114**), the data is first copied from the source drive into system memory, i.e., transferred from SSD **112**, via PCIe **104**, to CPU **102**, to system memory **106** (via a communication **120**). The data is then written from system memory to the destination drive, i.e., transferred from system memory **106** to CPU **102** and, via PCIe **304**, to SSD **114** (via a communication **122**). Thus, the host CPU and system memory are involved in the transfer of data from the source storage drive to the destination storage drive, which can increase the latency and inefficiency of the overall storage system.

FIG. **1**B illustrates an exemplary environment **130** with a data transfer between storage drives in different storage servers, in accordance with the prior art. Environment **130** can include an Ethernet switch **160** and a cluster of servers, where each server can include a CPU and a system memory, and be associated with multiple SSDs and a network interface card (NIC). For example, a first server **101** can include: a CPU **102**, an associated PCIe interface **104**, and an associated system memory **106**; one or more SSDs, such as an SSD **112**; and a NIC **132**. A second server **141** can include: a CPU **142**, an associated PCIe interface **144**, and an associated system memory **146**; one or more SSDs, such as an SSD **154**; and a NIC **152**. CPU **102** can communicate with SSD **112** via PCIe interface **104**, and CPU **142** can communicate with SSD **154** via PCIe interface **144**. The two depicted servers **101** and **141** can communicate with each other through Ethernet switch **160** via their respective NICs **132** and **152**.

During operation, in order to move data from one drive in the first server to another drive in the second server (e.g., from a source drive such as SSD **112** of server **101** to a destination drive such as SSD **154** of server **141**), the data is first copied from the source drive into system memory of the first server, i.e., transferred from SSD **112**, via PCIe **104**, to CPU **102**, to system memory **106** (via a communication path **160**). The data is then written from system memory to

NIC **132**, i.e., transferred from system memory **106** to CPU **102** and, via PCIe **104**, to NIC **132** (via a communication path **162**). NIC **132** can generate formatting information for the data, and perform other packet processing, data reordering, and concatenation operations.

NIC **132** can transfer the formatted data (e.g., formatting information and payload) to Ethernet switch **160** (via a communication **164**), and, based on the formatting information, Ethernet switch **160** can transfer the data to NIC **152** (via a communication **168**). NIC **152** can perform packet processing, data reordering, and concatenation operations. NIC **152** can send the data to be copied into system memory of the second server, i.e., transferred from NIC **152**, via PCIe **144**, to CPU **142**, to system memory **146** (via a communication path **170**). The data is then written from system memory to the destination drive, i.e., transferred from system memory **146** to CPU **142** and, via PCIe **144**, to SSD **154** (via a communication path **172**).

Thus, in environment **130**, the host CPU and system memory of both servers are involved in the transfer of data from the source storage drive to the destination storage drive, which can increase the latency and inefficiency of the overall storage system. In addition, the NICs of both servers can consume a non-trivial amount of time, energy, bandwidth, and other resources on packet processing, data reordering, concatenation, and other operations related to formatting and processing network packets. These operations can further increase the latency and inefficiency of the overall storage system.

Moreover, in the storage cluster depicted in environment **130**, the system can experience a non-trivial amount of traffic due to, e.g., managing data replicas, rebalancing data, etc. Moving multiple copies of data within the storage cluster can result in a performance bottleneck due to the latency involved in memory copy operations, as described above.

Exemplary Environment with Separate Control and Data Paths

FIG. **2** illustrates an exemplary environment **200** with separate control and data paths, which facilitates bypassing system memory, in accordance with an embodiment of the present application. Environment **200** can include: a host **202** with a local storage engine **210**; a NIC **230**; and SSDs **240**, **242**, and **246**. Local storage engine can include: a network engine **214**; a chunk organization module **212**; a local file system **216**; a flash translation layer (FTL) module **218**; and a Non-Volatile Memory Express (NVMe) driver **220**.

NIC **230** can store data as formatted data which includes formatting information and a payload. For example, payloads **232**, **234**, and **236** are indicated in FIG. **2** with left-slanting diagonal lines. Assume that metadata **250** is associated with the data indicated by payload **234** in NIC **230**. NIC **230** can send metadata **250** to host **202** for processing, and host **202**, after processing the metadata as described below, can send a physical block address (PBA) and metadata back to SSDs **240-246** (via a control path **262**). At the same or a similar time, NIC **230** can send the payload data itself directly to SSDs **240-246** (e.g., via a data path **260**).

Local storage engine **210** can perform a series of operations on metadata **250**. Upon receiving metadata **250** from NIC **230**, network engine **214** can generate management information, e.g., an order, a merged size, and other metadata for the data indicated by payload **234**. Network engine **214** can send management information **252** to chunk organization module **212**.

Chunk organization module **212** can group received network packets into multiple chunks in parallel, and can send chunk metadata **254** to local file system **216**. Local file system **216** can use chunk metadata **254** to allocate the logical extent (e.g., a range of logical block addresses (LBAs)) to accommodate the data, and can send LBA range/metadata **256** to FTL module **218**.

FTL module **218** can receive the incoming LBAs, including LBAs allocated to chunks associated with the data indicated by payload **234**, from multiple chunks in a random order, which is similar to the pattern associated with a random write operation. FTL module **218** can implement the mapping of the LBAs to physical block addresses (PBAs), e.g., by generating or mapping PBAs for the incoming LBAs, and storing the mapping in a data structure. FTL module **218** can send PBA/metadata **258** to NVMe driver **220**, which can perform any necessary data processing, and can send PBA/metadata **258** to controllers (not shown) of SSDs **240-246**, via control path **262**.

The PBA and metadata information received by controllers of SSDs **240-246** via control path **262**, along with the payload data received by the controllers of SSDs **240-246** via control path **260**, can accomplish the programming of the NAND flash in SSDs **240-246**. Thus, the operations and communications depicted in environment **200** demonstrate how the local storage engine collaborating with the SSD controller for metadata/data transmission can result in an improved system for both data transmission and storage efficiency.

Data Movement from a NIC to a Storage Drive

FIG. **3** illustrates an exemplary environment **300** with data movement from a network interface card to a storage drive, in accordance with an embodiment of the present application. Environment **300** can include: a NIC memory **310** (which is set as host memory); an SSD controller write cache **340**; and a non-volatile memory **370**, such as NAND flash storage modules, units, or components **372**, **374**, and **376**. NIC memory **310** can store formatted data, which can include formatting information and a payload. For example, NIC memory can store network packets as: formatting information **322** for a payload or application data indicated by a packet_1 **324**; formatting information **326** for a payload or application data indicated by a packet_2 **328**; and formatting information **330** for a payload or application data indicated by a packet_n **332**.

Each network packet can include formatting information and a payload or application data. For example, formatting information **326** and packet_2 **328** can include: a frame header **312**, an Internet Protocol (IP) header **314**, and a Transmission Control Protocol (TCP) header **316** which are part of formatting information **326**, as indicated by right-slanting diagonal lines; and application data **318**, which can correspond to the payload of packet_2 **328**.

The SSD controller can store data in write cache **340** in write groups of a predetermined size, and when the data stored in a given write group reaches the predetermined size, the SSD controller can write the data in the given write group to the NAND flash. For example, write cache **340** can include a write group_1 **350** and a write group_2 **360**. Environment **300** can depict that the payload or application data indicated by packet_1 **324** has been written as a data packet_1 **352** to write group_1 **350** of write cache **340**. Another payload can then be written to write group_1 **350**, as indicated by packet_2 **328** being written to write group_1 **350** as a data packet_2 **354** (via a communication **370**).

The system can determine that the data stored in write group _1 **350** meets or has reached a predetermined group

size, and can write the data to non-volatile memory **370** (i.e., NAND flash **372-376**). The predetermined group size can be based on, e.g., a size of a page in the NAND flash or a number of available channels for processing data in a parallel manner.

Exemplary Environment for Data Transfer: Single Server Scenario and Storage Cluster Scenario

FIG. **4**A illustrates an exemplary environment **400** with a data transfer between storage drives in a same storage server, which facilitates bypassing system memory, in accordance with an embodiment of the present application. Environment **400** can include: a central processing unit (CPU) **402**, an associated Peripheral Component Interconnect Express (PCIe) interface **404**, and an associated system memory **406**; and solid-state drives (SSDs) **412**, **414**, and **416**. A respective SSD can expose a portion of its memory as system memory, which allows other SSDs (or a NIC) in the same server to directly retrieve data from the exposed system memory of the respective SSD. The other SSDs can also send data directly to this exposed system memory on the respective SSD.

For example, during operation, the system can allocate, in the volatile memory of SSD **412**, a first region (system memory or sysmem) **413** to be accessed directly by a second storage drive (such as SSD **414** via a communication **420**) or a first NIC (as described below in relation to FIG. **4**B). In addition, SSD **416** (or SSD **414**) can send or write data directly to the allocated first region (system memory) **413** of SSD **412** (via, e.g., a communication **422**). This allows data to be retrieved from or written to SSD **412** while bypassing system memory **406**, thus eliminating the need to copy the data into the system memory or DIMM of the server itself (which challenge is described above in relation to the prior art environment of FIG. **1**A).

FIG. **4**B illustrates an exemplary environment **430** with a data transfer between storage drives in different storage servers, which facilitates bypassing system memory, in accordance with an embodiment of the present application. Environment **430** can include an Ethernet switch **460** and a cluster of servers, where each server can include a CPU and a system memory, and be associated with multiple SSDs and a network interface card (NIC). For example, a first server **401** can include: a CPU **402**, an associated PCIe interface **404**, and an associated system memory **406**; one or more SSDs, such as an SSD **412**; and a NIC **432**. A second server **441** can include: a CPU **442**, an associated PCIe interface **444**, and an associated system memory **446**; one or more SSDs, such as an SSD **454**; and a NIC **452**. The two depicted servers **401** and **441** can communicate with each other through Ethernet switch **460** via their respective NICs **432** and **452**.

A first SSD of the first server can expose a portion of its memory as system memory, which allows a first NIC of the first server to directly retrieve data from the exposed system memory of the respective SSD. The first NIC can send the retrieved data, along with network formatting information, to a second NIC of a second server. A second SSD of the second server can retrieve the data directly from the second NIC (as described above in relation to FIG. **3**.

For example, during operation, the system can allocate, in the volatile memory of SSD **412**, a first region (system memory or sysmem) **413** to be accessed directly by NIC **432** (or by other SSDs of server **401**). SSD **412** can store data in the allocated first region sysmem **413**. SSD **454** can generate a request to retrieve data from SSD **412** (or the system can determine that SSD **412** is to send data to SSD **454**). NIC **432** can retrieve the requested data from sysmem **413** of SSD **412** (via a communication **470**). NIC **432** can generate formatting information for the data, and perform other packet processing, data reordering, and concatenation operations, i.e., by adjusting the data into a predefined format such as described above in relation to FIG. **3**.

NIC **432** can transfer the formatted data (including formatting information and payload) to Ethernet switch **460** (via a communication **472**), and, based on the formatting information, Ethernet switch **460** can transfer the data to NIC **452** (via a communication **474**). NIC **452** can perform packet processing, data reordering, and concatenation operations. NIC **452** can store the data as formatted data which includes formatting information and a payload. NIC **452** can send the payload data directly to SSD **454** (via communications **476**, which can correspond to the operations described above in relation to FIG. **2**). SSD **454** can also allocate a region (not shown) of its volatile memory as a system memory which can be accessed directly by NIC **452** or other SSDs of server **441**. Moreover, SSD **454** can retrieve the payload data directly from NIC **452** by accessing the formatted data and selecting only the portions of payload data, e.g., by dropping the formatting information or formatting bits (via communications **476**). SSD **454** can then group the data and write the data to its NAND flash based on the pages and PBAs as assigned by the FTL at the host side, as described above in relation to FIG. **2**.

Thus, FIG. **4**B depicts an environment or system which allows data to be retrieved from (or written to) SSD **412** by SSD **454** while bypassing both system memory **406** and **446**, thus eliminating the need to copy the data into the system memory or DIMM of both servers **401** and **441** (which challenge is described above in relation to the prior art environment of FIG. **1**B).

Controller Operations for Ensuring Data Quality

FIG. **5**A illustrates an exemplary environment **500** for data access with a cyclic redundancy check (CRC) in a storage controller, in accordance with an embodiment of the present application. Environment **500** can include a storage controller with associated components or modules, and can also include a volatile memory of a storage device and non-volatile memory of the storage device. The storage controller can include: a PCIe physical layer (PHY) **510**; an NVMe controller **512**; a DDR controller **514**; a cyclic redundancy check (CRC) module **518**; and a flash controller **520** with an error correction code (ECC) encoding/decoding module **522**. DDR controller **514** can communicate with a volatile memory DDR **516** and an allocated region sysmem **517** of volatile memory **516**. Note that sysmem **517** can serve as the allocated and exposed region of system memory which can be directly accessed by other SSDs or the NIC in the same server. For example, sysmem **517** can correspond to sysmem **413** of SSD **412** of FIG. **4**A, as the allocated region from which data can be directly retrieved (e.g., communication **420**) or to which data can be directly written (e.g., communication **420**) by a storage device of the same server. Sysmem **517** can also correspond to sysmem **413** of FIG. **4**B, as the allocated region from which data can be directly retrieved by a NIC of the same server (e.g., communication **470**).

Data can be sent to or received from host **530**, and can also be sent to or received from NAND flash **532**. For example, as indicated by a communication path **534**, data can be received from host **530**. This data can be the data fetched directly from the allocated sysmem which bypasses the server's system memory or DIMM. The fetched data can travel through PCIe PHY **510** to NVMe controller **512**, and NVMe controller **512** can operate to process the data as

needed. CRC **518** can perform a CRC check on the data, which can then be passed via DDR controller **514** to be temporarily buffered, with power loss protection, in sysmem **517** of DDR **516** (as indicated by communication path **534**).

Subsequently, as indicated by a communication path **536**, the data can be sent to the NAND flash. When reading out the stored data from sysmem **517** of DDR **516**, the data is passed via DDR controller **514** back to CRC **518**, which can check the CRC to ensure the integrity, correctness, or accuracy of the data. CRC **518** can send the CRC-checked data to ECC **522** of flash controller **520**. ECC **522** can perform ECC encoding on the data, and can send the ECC-encoded data to the NAND flash (via **532** as part of communication path **536**).

FIG. **5**B illustrates an exemplary environment **540** for data access with a CRC in a storage controller, in accordance with an embodiment of the present application. Environment **540** can include a CRC module **542**, a memory module **544**, and a CRC module **546**. CRC modules **542** and **546** can correspond to CRC module **518** of FIG. **5**A; memory **544** can correspond to sysmem **517** of DDR **516** of FIG. **5**A; a path **554** can correspond to path **534** of FIG. **5**A; and a path **556** can correspond to path **536** of FIG. **5**A.

Environment **540** depicts a high-level view of the communications described above in relation to FIG. **5**A. During operation, the system (by CRC **542**) can receive data to be stored in non-volatile memory via path **554**. CRC **542** can perform a first redundancy check and send the CRC data to memory **544** (via path **554**). The system can store the CRC data in memory **544**, and can subsequently retrieve (by CRC **546**) the stored CRC data from memory **544**. CRC **546** can perform a second redundancy check, and send the CRC-checked data onwards, e.g., to ECC **522** (via path **556**).

Method for Facilitating Data Movement by Bypassing System Memory: Single Server Scenario and Storage Cluster Scenario

FIG. **6**A presents a flowchart **600** illustrating a method for facilitating data movement while bypassing system memory, including a data transfer between storage drives in a same storage server, in accordance with an embodiment of the present application. During operation, the system allocates, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive or a first network interface card (NIC), wherein the first storage drive, the second storage drive, and the first NIC are associated with a first server (operation **602**). The system stores data in the first region of the first storage drive (operation **604**). Responsive to receiving a first request from the second storage drive to read the data, the system transmits, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server (operation **606**). Responsive to receiving, from a third storage drive associated with a second server, a second request to read the data, the system retrieves, by the first NIC, the data stored in the first region while bypassing the system memory of the first server (operation **608**). The operation continues at Label A of FIG. **6**B.

FIG. **6**B presents a flowchart **620** illustrating a method for facilitating data movement while bypassing system memory, including a data transfer between storage drives in different storage servers, in accordance with an embodiment of the present application. The system stores, by the first NIC, the data as formatted data which includes formatting information and a payload (operation **622**). The system sends, by the first NIC to a second NIC associated with the second server, the formatted data (operation **624**). The system stores, by the second NIC, the formatted data (operation **626**). The system sends, by the second NIC to a local storage engine associated with the second server, metadata associated with the data (operation **628**).

The system generates, by the local storage engine, management information which includes a physical block address of a non-volatile memory of the third storage drive to which the data is to be written (operation **630**). The system sends, by the local storage engine, the management information to the third storage drive (operation **632**). The system sends, by the second NIC, the payload to the third storage drive (operation **634**). The system receives, by the third storage drive, the management information from the local storage engine and the payload from the second NIC (operation **636**). The system writes, by the third storage drive, the data to the non-volatile memory of the third storage drive based on the received management information (operation **638**), and the operation returns.

Method for Facilitating Data Movement by Writing Data in Groups to a Non-Volatile Memory

FIG. **7** presents a flowchart **700** illustrating a method for facilitating data movement while bypassing system memory, including writing data in groups to a non-volatile memory, in accordance with an embodiment of the present application. During operation, the system stores, by the third storage drive, in a buffer of the third storage drive, the payload as part of a group (operation **702**). The system stores other payloads in the group, wherein the other payloads are associated with other management information (operation **704**). The system determines whether a size of the payload and the other payloads meets a predetermined group size (operation **706**). If it does not (decision **708**), the operation returns to operation **704**. If it does (decision **708**), the system writes, from the buffer of the third storage drive to the non-volatile memory, the payload and the other payloads of the group (operation **710**). Writing the payload and the other payloads of the group to the non-volatile memory can be based on the PBA, metadata, and other management information received from a local storage engine of a host, as described above in relation to FIG. **2**.

FIG. **8** presents a flowchart **800** illustrating a method for facilitating data movement while bypassing system memory, including operations to ensure data integrity, in accordance with an embodiment of the present application. During operation, the system receives, by a controller of the third storage drive, the data (operation **802**). The controller can include a Non-Volatile Memory Express (NVMe) controller, a double data rate (DDR) controller associated with the volatile memory, a cyclic redundancy check (CRC) module, and a flash controller. The flash controller can include an error correction code (ECC) encoding/decoding module. The system performs, by the CRC module, a first redundancy check on the received data to obtain CRC data (operation **804**). The system stores, by the DDR controller in the first region of the volatile memory, the CRC data (operation **806**). The system determines to write the stored CRC data from the first region of the volatile memory to the non-volatile memory (operation **808**). This determination can be based on a size of a write group in a write cache or buffer of the SSD controller, as described above in relation to FIG. **3**.

The system retrieves, by the DDR controller, the stored CRC data (operation **810**). The system performs, by the CRC module, a second redundancy check on the retrieved CRC data to obtain CRC-checked data (operation **812**). Responsive to verifying the CRC-checked data, the system encodes, by the ECC encoding/decoding module of the flash controller, the CRC-checked data to obtain ECC-encoded

data (operation **814**). The system writes the ECC-encoded data to the non-volatile memory (operation **816**), and the operation returns.

Exemplary Computer System and Apparatus

FIG. **9** illustrates an exemplary computer system **900** that facilitates data movement while bypassing system memory, in accordance with an embodiment of the present application. Computer system **900** includes a processor **902**, a volatile memory **906**, and a storage device **908**. In some embodiments, computer system **900** can include a controller **904** (indicated by the dashed lines). Volatile memory **906** can include, e.g., random access memory (RAM), that serves as a managed memory, and can be used to store one or more memory pools. Storage device **908** can include persistent storage which can be managed or accessed via processor **902** (or controller **904**). Furthermore, computer system **900** can be coupled to peripheral input/output (I/O) user devices **910**, e.g., a display device **911**, a keyboard **912**, and a pointing device **914**. Storage device **908** can store an operating system **916**, a content-processing system **918**, and data **936**.

Content-processing system **918** can include instructions, which when executed by computer system **900**, can cause computer system **900** or processor **902** to perform methods and/or processes described in this disclosure. Specifically, content-processing system **918** can include instructions for receiving and transmitting data packets, including data to be read or written, an input/output (I/O) request (e.g., a read request or a write request), metadata, management information, a PBA, an LBA, a payload, formatting information, CRC data, and ECC-encoded data (communication module **920**).

Content-processing system **918** can further include instructions for allocating, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive or a first network interface card (NIC), wherein the first storage drive, the second storage drive, and the first NIC are associated with a first server (sysmem region-managing module **922**). Content-processing system **918** can include instructions for storing data in the first region of the first storage drive (data-writing module **930**). Content-processing system **918** can include instructions for, responsive to receiving a first request from the second storage drive to read the data (communication module **920**), transmitting, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server (communication module **920** and sysmem region-managing module **922**). Content-processing system **918** can also include instructions for, responsive to receiving, from a third storage drive associated with a second server, a second request to read the data (communication module **920**), retrieving, by the first NIC, the data stored in the first region while bypassing the system memory of the first server (data-reading module **928** and sysmem region-managing module **922**).

Content-processing system **918** can additionally include instructions for storing, by the first NIC, the data as formatted data which includes formatting information and a payload (packet-formatting module **924**). Content-processing system **918** can include instructions for sending, by the first NIC to a second NIC associated with the second server, the formatted data (communication module **920**). Content-processing system **918** can include instructions for storing, by the second NIC, the formatted data (data-writing module **930**). Content-processing system **918** can include instructions for sending, by the second NIC to a local storage engine associated with the second server, metadata associated with the data (communication module **920** and metadata-managing module **926**). Content-processing system **918** can also include instructions for generating, by the local storage engine, management information which includes a physical block address of a non-volatile memory of the third storage drive to which the data is to be written (metadata-managing module **920**). Content-processing system **918** can include instructions for sending, by the local storage engine, the management information to the third storage drive (communication module **920** and metadata-managing module **926**). Content-processing system **918** can include instructions for sending, by the second NIC, the payload to the third storage drive (communication module **920**). Content-processing system **918** can include instructions for receiving, by the third storage drive, the management information from the local storage engine and the payload from the second NIC (communication module **920**). Content-processing system **918** can include instructions for writing, by the third storage drive, the data to the non-volatile memory of the third storage drive based on the received management information (data-writing module **930**). Content-processing system **918** can include instructions for performing the operations described above in relation to FIG. **2**.

Content-processing system **918** can further include instructions for storing, by the third storage drive, in a buffer of the third storage drive, the payload as part of a group (data-writing module **930** and cache-managing module **932**). Content-processing system **918** can include instructions for storing other payloads in the group, wherein the other payloads are associated with other management information (data-writing module **930** and cache-managing module **932**). Content-processing system **918** can include instructions for determining that a size of the payload and the other payloads meets a predetermined group size (cache-managing module **932**). Content-processing system **918** can include instructions for writing, from the buffer of the third storage drive to the non-volatile memory, the payload and the other payloads of the group (data-writing module **930**). Content-processing system **918** can include instructions for performing the operations described above in relation to FIG. **7**.

Content-processing system **918** can also include instructions for receiving, by a controller of the third storage drive, the data (communication module **920**). Content-processing system **918** can include instructions for performing, by the CRC module, a first redundancy check on the received data to obtain CRC data (error-detecting module **934**). Content-processing system **918** can include instructions for storing, by the DDR controller in the first region of the volatile memory, the CRC data (data-writing module **930** and sysmem region-managing module **922**). Content-processing system **918** can include instructions for determining to write the stored CRC data from the first region of the volatile memory to the non-volatile memory (sysmem region-managing module **922**). Content-processing system **918** can include instructions for retrieving, by the DDR controller, the stored CRC data (data-reading module **928**). Content-processing system **918** can include instructions for performing, by the CRC module, a second redundancy check to obtain CRC-checked data (error-detecting module **934**). Content-processing system **918** can include instructions for, responsive to verifying the CRC checked data, encoding, by the ECC encoding/decoding module of the flash controller, the CRC-checked data to obtain ECC-encoded data (error-detecting module **934**). Content-processing system **918** can include instructions for writing the ECC-encoded data to the non-volatile memory (data-writing module **930**). Content-

processing system **918** can include instructions for performing the operations described above in relation to FIG. **8**.

Data **936** can include any data that is required as input or generated as output by the methods and/or processes described in this disclosure. Specifically, data **936** can store at least: data; a request; a read request; a write request; an input/output (I/O) request; data or metadata associated with a read request, a write request, or an I/O request; formatted data; encoded data; CRC data; CRC-checked data; ECC-encoded data; an indicator or identifier of a storage drive, a local storage engine, a NIC, a switch, or a server; formatting information; a frame header; an IP header; a TCP header; a payload; application data; user data; a network packet; metadata; management information; a logical block address (LBA); a physical block address (PBA); an indicator of a region or an allocated region of a volatile memory; a chunk of data; chunk metadata; a logical extent or range of LBAs; a group of data; a predetermined group size; a size of a payload; and a size of multiple payloads stored in a group.

FIG. **10** illustrates an exemplary apparatus **1000** that facilitates data movement while bypassing system memory, in accordance with an embodiment of the present application. Apparatus **1000** can comprise a plurality of units or apparatuses which may communicate with one another via a wired, wireless, quantum light, or electrical communication channel. Apparatus **1000** may be realized using one or more integrated circuits, and may include fewer or more units or apparatuses than those shown in FIG. **10**. Furthermore, apparatus **1000** may be integrated in a computer system, or realized as a separate device or devices capable of communicating with other computer systems and/or devices.

Apparatus **1000** can comprise modules or units **1002-1016** which are configured to perform functions or operations similar to modules **920-934** of computer system **900** of FIG. **9**, including: a communication unit **1002**; a sysmem region-managing unit **1004**; a packet-formatting unit **1006**; a metadata-managing unit **1008**; a data-reading unit **1010**; a data-writing unit **1012**; a cache-managing unit **1014**; and an error-detecting unit **1016**.

The data structures and code described in this detailed description are typically stored on a computer-readable storage medium, which may be any device or medium that can store code and/or data for use by a computer system. The computer-readable storage medium includes, but is not limited to, volatile memory, non-volatile memory, magnetic and optical storage devices such as disk drives, magnetic tape, CDs (compact discs), DVDs (digital versatile discs or digital video discs), or other media capable of storing computer-readable media now known or later developed.

The methods and processes described in the detailed description section can be embodied as code and/or data, which can be stored in a computer-readable storage medium as described above. When a computer system reads and executes the code and/or data stored on the computer-readable storage medium, the computer system performs the methods and processes embodied as data structures and code and stored within the computer-readable storage medium.

Furthermore, the methods and processes described above can be included in hardware modules. For example, the hardware modules can include, but are not limited to, application-specific integrated circuit (ASIC) chips, field-programmable gate arrays (FPGAs), and other programmable-logic devices now known or later developed. When the hardware modules are activated, the hardware modules perform the methods and processes included within the hardware modules.

The foregoing embodiments described herein have been presented for purposes of illustration and description only. They are not intended to be exhaustive or to limit the embodiments described herein to the forms disclosed. Accordingly, many modifications and variations will be apparent to practitioners skilled in the art. Additionally, the above disclosure is not intended to limit the embodiments described herein. The scope of the embodiments described herein is defined by the appended claims.

What is claimed is:

1. A computer-implemented method, comprising:

allocating, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive,

wherein the first storage drive and the second storage drive are associated with a first server, wherein the first region of the first storage drive is to be further accessed by a third storage drive via a first network interface card (NIC), wherein the first NIC is associated with the first server, and wherein the third storage drive is associated with a second server;

storing data in the first region of the first storage drive;

responsive to receiving a first request from the second storage drive to read the data, transmitting, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server;

responsive to receiving, from the third storage drive, a second request to read the data, retrieving, by the first NIC, the data stored in the first region while bypassing the system memory of the first server;

sending, by the first NIC to a second NIC associated with the second server, the data as formatted data which includes formatting information and a payload;

sending, by the second NIC to a local storage engine associated with the second server, metadata associated with the data, which causes the local storage engine to:

allocate, by a file system of the local storage engine, a logical extent or a range of logical block addresses (LBAs) based on metadata associated with multiple chunks of data;

send, by the file system to a flash translation layer (FTL) module of the local storage engine, the allocated LBAs;

generate, by the FTL module, physical block addresses (PBAs) mapped to the allocated LBAs, wherein management information includes the PBAs, the metadata, and one or more of an order and a merged size; and

transmit, to the third storage drive, the management information;

receiving, by the third storage drive, the management information from the local storage engine and the payload from the second NIC; and

writing, by the third storage drive, the data to the non-volatile memory of the third storage drive based on the received management information.

2. The method of claim **1**, further comprising:

storing, by the first NIC, the data as formatted data which includes formatting information and a payload;

storing, by the second NIC, the formatted data; and

sending, by the second NIC, the payload to the third storage drive.

3. The method of claim **2**,

wherein the formatting information includes one or more of a frame header, an Internet Protocol (IP) header, and a Transmission Control Protocol (TCP) header,

wherein the payload includes one or more of application data and user data, and

wherein sending, by the first NIC to the second NIC, the formatted data further involves sending the formatted data through an Ethernet switch.

4. The method of claim **2**, further comprising:

setting, in the second NIC, a second region of a volatile memory of the second NIC as a host memory which is directly accessible by the third storage drive; and

storing, by the second NIC, the formatted data in the second region of the second NIC.

5. The method of claim **1**, wherein sending, by the second NIC to the local storage engine associated with the second server, the metadata associated with the data further causes the local storage engine to:

generate, by a network engine of the local storage engine, the management information, which includes one or more of the order and the merged size;

group, by a chunk organization module of the local storage engine, multiple chunks of data in parallel;

receive, by the FTL module, the allocated LBAs;

transmit, by the FTL module to a Non-Volatile Memory Express (NVMe) driver, the PBAs and the metadata; and

transmit, by the NVMe driver to a controller of the third storage drive, the PBAs and the metadata.

6. The method of claim **1**, wherein writing, by the third storage drive, the data to the non-volatile memory based on the received management information comprises:

storing, by the third storage drive, in a buffer of the third storage drive, the payload as part of a group;

storing other payloads in the group, wherein the other payloads are associated with other management information;

determining that a size of the payload and the other payloads meets a predetermined group size; and

writing, from the buffer of the third storage drive to the non-volatile memory, the payload and the other payloads of the group.

7. The method of claim **1**, wherein writing, by the third storage drive, the data to the non-volatile memory comprises:

receiving, by a controller of the third storage drive, the data,

wherein the controller includes a Non-Volatile Memory Express (NVMe) controller, a double data rate (DDR) controller associated with the volatile memory, a cyclic redundancy check (CRC) module, and a flash controller, wherein the flash controller includes an error correction code (ECC) encoding/decoding module;

performing, by the CRC module, a first redundancy check on the received data to obtain CRC data;

storing, by the DDR controller in the first region of the volatile memory, the CRC data;

determining to write the stored CRC data from the first region of the volatile memory to the non-volatile memory;

retrieving, by the DDR controller, the stored CRC data;

performing, by the CRC module, a second redundancy check on the retrieved CRC data to obtain CRC-checked data;

responsive to verifying the CRC-checked data, encoding, by the ECC encoding/decoding module of the flash controller, the CRC-checked data to obtain ECC-encoded data; and

writing the ECC-encoded data to the non-volatile memory.

8. The method of claim **1**, wherein subsequent to the first storage drive transmitting to the second storage drive the data stored in the first region while bypassing the system memory of the first server, the method further comprises:

retrieving, by the second storage drive, the data stored in the first region while bypassing the system memory of the first server.

9. A computer system, comprising:

a processor; and

a memory coupled to the processor and storing instructions which, when executed by the processor, cause the processor to perform a method, the method comprising:

allocating, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive,

wherein the first storage drive and the second storage drive are associated with a first server, wherein the first region of the first storage drive is to be further accessed by a third storage drive via a first network interface card (NIC), wherein the first NIC is associated with the first server, and wherein the third storage drive is associated with a second server;

storing data in the first region of the first storage drive;

responsive to receiving a first request from the second storage drive to read the data, transmitting, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server;

responsive to receiving, from the third storage drive, a second request to read the data, retrieving, by the first NIC, the data stored in the first region while bypassing the system memory of the first server;

sending, by the first NIC to a second NIC associated with the second server, the data as formatted data which includes formatting information and a payload;

sending, by the second NIC to a local storage engine associated with the second server, metadata associated with the data, which causes the local storage engine to:

allocate, by a file system of the local storage engine, a logical extent or a range of logical block addresses (LBAs) based on metadata associated with multiple chunks of data;

send, by the file system to a flash translation layer (FTL) module of the local storage engine, the allocated LBAs;

generate, by the FTL module, physical block addresses (PBAs) mapped to the allocated LBAs, wherein management information includes the PBAs, the metadata, and one or more of an order and a merged size; and

transmit, to the third storage drive, the management information;

receiving, by the third storage drive, the management information from the local storage engine and the payload from the second NIC; and

writing, by the third storage drive, the data to the non-volatile memory of the third storage drive based on the received management information.

10. The computer system of claim **9**, wherein the method further comprises:

storing, by the first NIC, the data as formatted data which includes formatting information and a payload;

storing, by the second NIC, the formatted data;

sending, by the second NIC, the payload to the third storage drive.

11. The computer system of claim 10,

wherein the formatting information includes one or more of a frame header, an Internet Protocol (IP) header, and a Transmission Control Protocol (TCP) header,

wherein the payload includes one or more of application data and user data, and

wherein sending, by the first NIC to the second NIC, the formatted data further involves sending the formatted data through an Ethernet switch.

12. The computer system of claim 10, wherein the method further comprises:

setting, in the second NIC, a second region of a volatile memory of the second NIC as a host memory which is directly accessible by the third storage drive; and

storing, by the second NIC, the formatted data in the second region of the second NIC.

13. The computer system of claim 9, wherein sending, by the second NIC to the local storage engine associated with the second server, the metadata associated with the data further causes the local storage engine:

generate, by a network engine of the local storage engine, the management information, which includes one or more of the order and the merged size;

group, by a chunk organization module of the local storage engine, multiple chunks of data in parallel;

receive, by the FTL module, the allocated LBAs;

transmit, by the FTL module to a Non-Volatile Memory Express (NVMe) driver, the PBAs and the metadata; and

transmit, by the NVMe driver to a controller of the third storage drive, the PBAs and the metadata.

14. The computer system of claim 9, wherein writing, by the third storage drive, the data to the non-volatile memory based on the received management information comprises:

storing, by the third storage drive, in a buffer of the third storage drive, the payload as part of a group;

storing other payloads in the group, wherein the other payloads are associated with other management information;

determining that a size of the payload and the other payloads meets a predetermined group size; and

writing, from the buffer of the third storage drive to the non-volatile memory, the payload and the other payloads of the group.

15. The computer system of claim 9, wherein writing, by the third storage drive, the data to the non-volatile memory comprises:

receiving, by a controller of the third storage drive, the data,

wherein the controller includes a Non-Volatile Memory Express (NVMe) controller, a double data rate (DDR) controller associated with the volatile memory, a cyclic redundancy check (CRC) module, and a flash controller, wherein the flash controller includes an error correction code (ECC) encoding/decoding module;

performing, by the CRC module, a first redundancy check on the received data to obtain CRC data;

storing, by the DDR controller in the first region of the volatile memory, the CRC data;

determining to write the stored CRC data from the first region of the volatile memory to the non-volatile memory;

retrieving, by the DDR controller, the stored CRC data;

performing, by the CRC module, a second redundancy check on the retrieved CRC data to obtain CRC-checked data;

responsive to verifying the CRC-checked data, encoding, by the ECC encoding/decoding module of the flash controller, the CRC-checked data to obtain ECC-encoded data; and

writing the ECC-encoded data to the non-volatile memory.

16. An apparatus, comprising:

a region-managing module configured to allocate, in a volatile memory of a first storage drive, a first region to be accessed directly by a second storage drive or a first network interface card (NIC),

wherein the first storage drive, the second storage drive, and the first NIC are associated with a first server, wherein the first region of the first storage drive is to be further accessed by a third storage drive via a first network interface card (NIC), wherein the first NIC is associated with the first server, and wherein the third storage drive is associated with a second server;

a data-writing module configured to store data in the first region of the first storage drive;

a communication module configured receive a first request from the second storage drive to read the data,

wherein the data-writing module is configured to, responsive to the communication module receiving the first request, transmit, by the first storage drive to the second storage drive, the data stored in the first region while bypassing a system memory of the first server,

wherein the communication module is further configured to receive, from the third storage drive, a second request to read the data; and

a data-reading module configured to, responsive to the communication module receiving the second request, retrieve, by the first NIC, the data stored in the first region while bypassing the system memory of the first server,

wherein the communication module is further configured to:

send, by the first NIC to a second NIC associated with the second server, the data as formatted data which includes formatting information and a payload; and

send, by the second NIC to a local storage engine associated with the second server, metadata associated with the data,

wherein a metadata-managing unit is configured to, responsive to the second NIC sending the metadata to the local storage engine:

allocate, by a file system of the local storage engine, a logical extent or a range of logical block addresses (LBAs) based on metadata associated with multiple chunks of data;

send, by the file system to a flash translation layer (FTL) module of the local storage engine, the allocated LBAs;

generate, by the FTL module, physical block addresses (PBAs) mapped to the allocated LBAs, wherein management information includes the PBAs, the metadata, and one or more of an order and a merged size; and

transmit, to the third storage drive, the management information;

wherein the communication module is further configured to receive, by the third storage drive, the management information from the local storage engine and the payload from the second NIC, and

wherein the data-writing module is further configured to write, by the third storage drive, the data to the

non-volatile memory of the third storage drive based on the received management information.

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